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Title: A NEW SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON

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Los Alamos
NATIONAL LABORATORY

A NEW SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON

Martin Cooper, Los Alamos
Co-spokesperson for the EDM Project

for presentation to

FNAL Wine and Cheese Seminar

Batavia, Illinois

October 25, 2002

A New Search for the Neutron Electric Dipole Moment

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http://p25ext.lanl.gov/edm/edm.html

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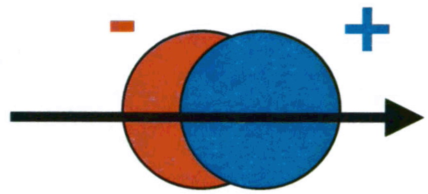
March 28, 2002

The Permanent EDM of the Neutron

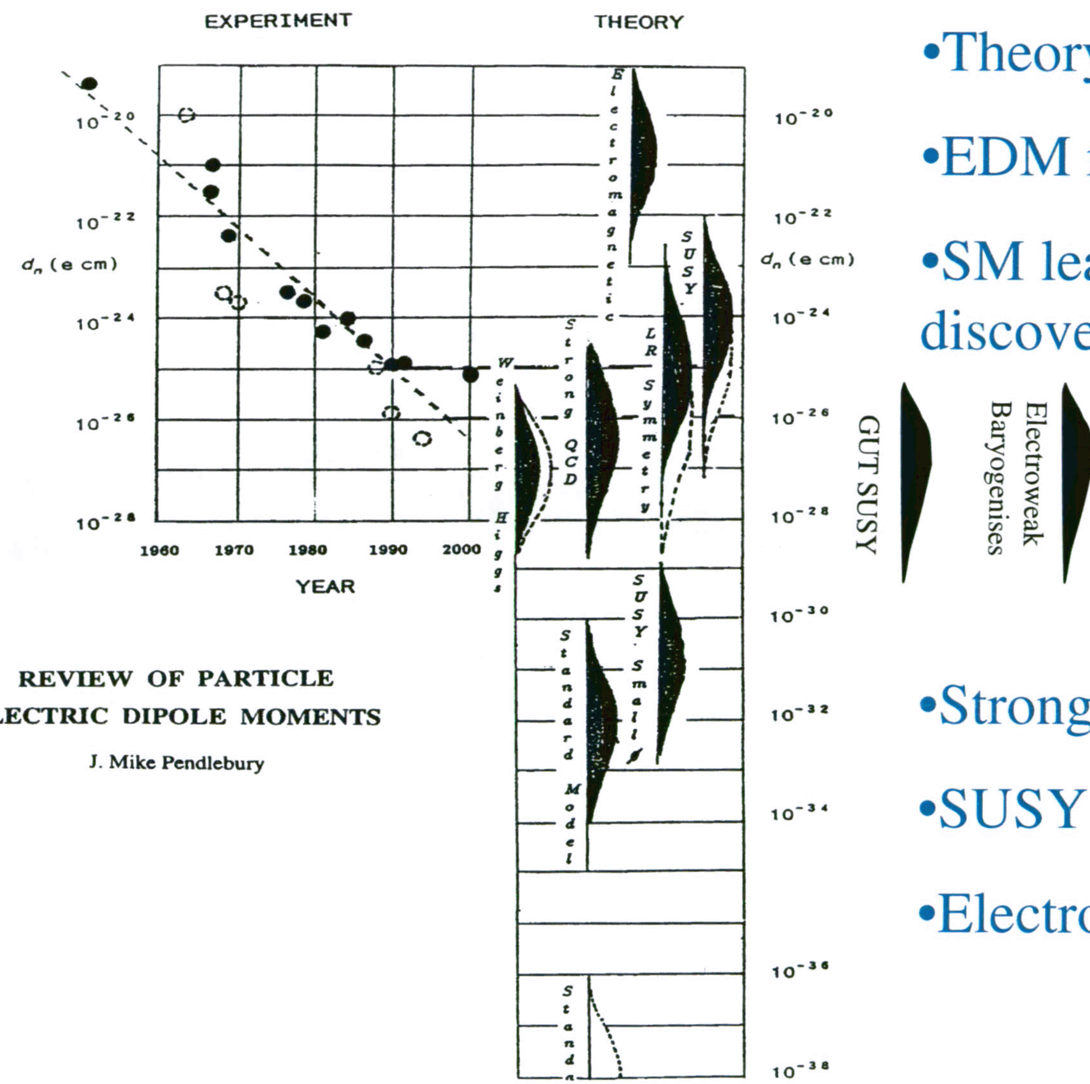
- A permanent EDM $\vec{d}$

$\vec{d} \bullet \vec{E}$



s = 1/2

- The current value is $< 6 \times 10^{-26}$ e•cm (90% C.L.)
- We hope to obtain roughly $< 10^{-28}$ e•cm with UCN in superfluid He

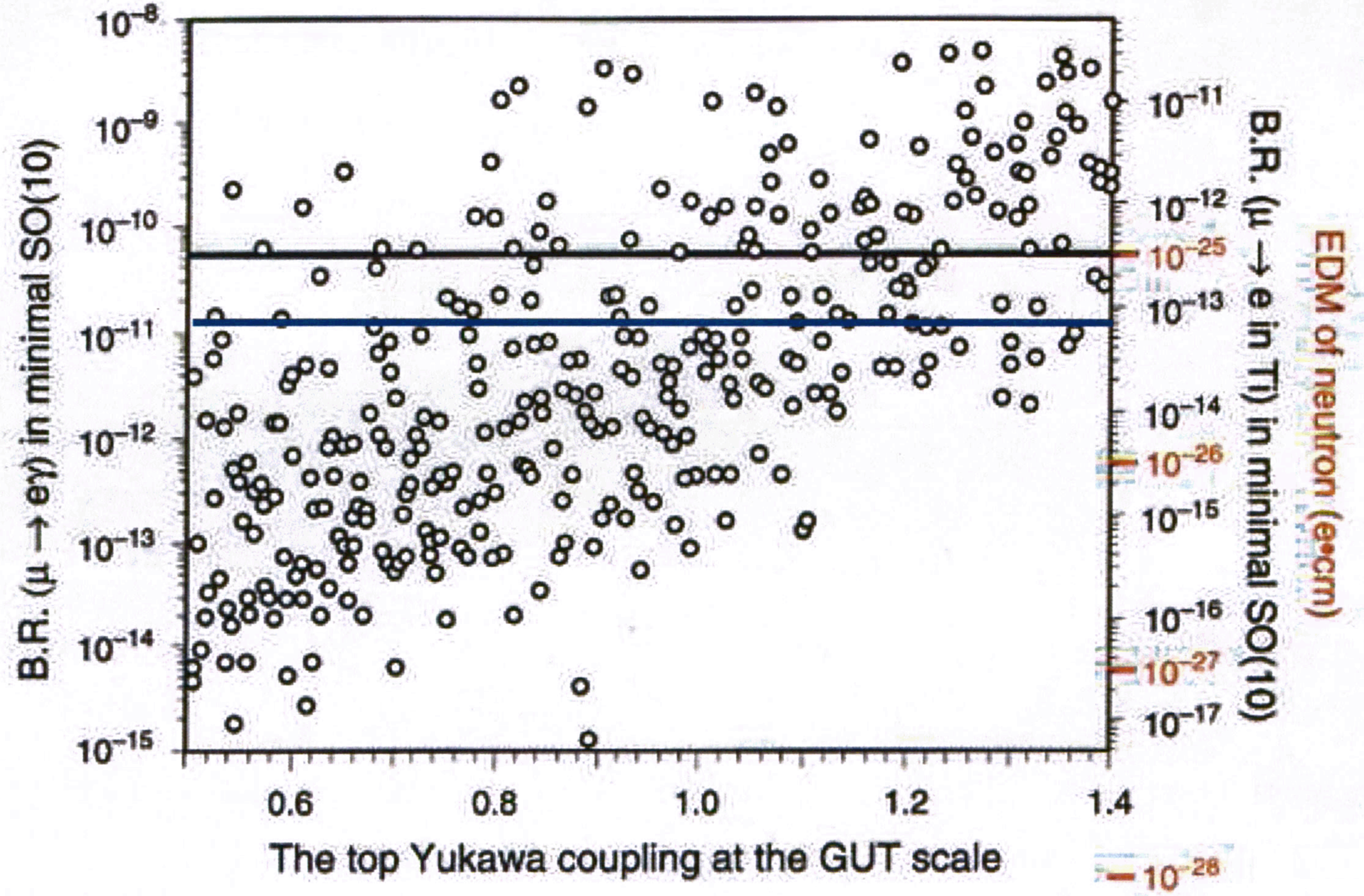


REVIEW OF PARTICLE ELECTRIC DIPOLE MOMENTS

J. Mike Pendlebury

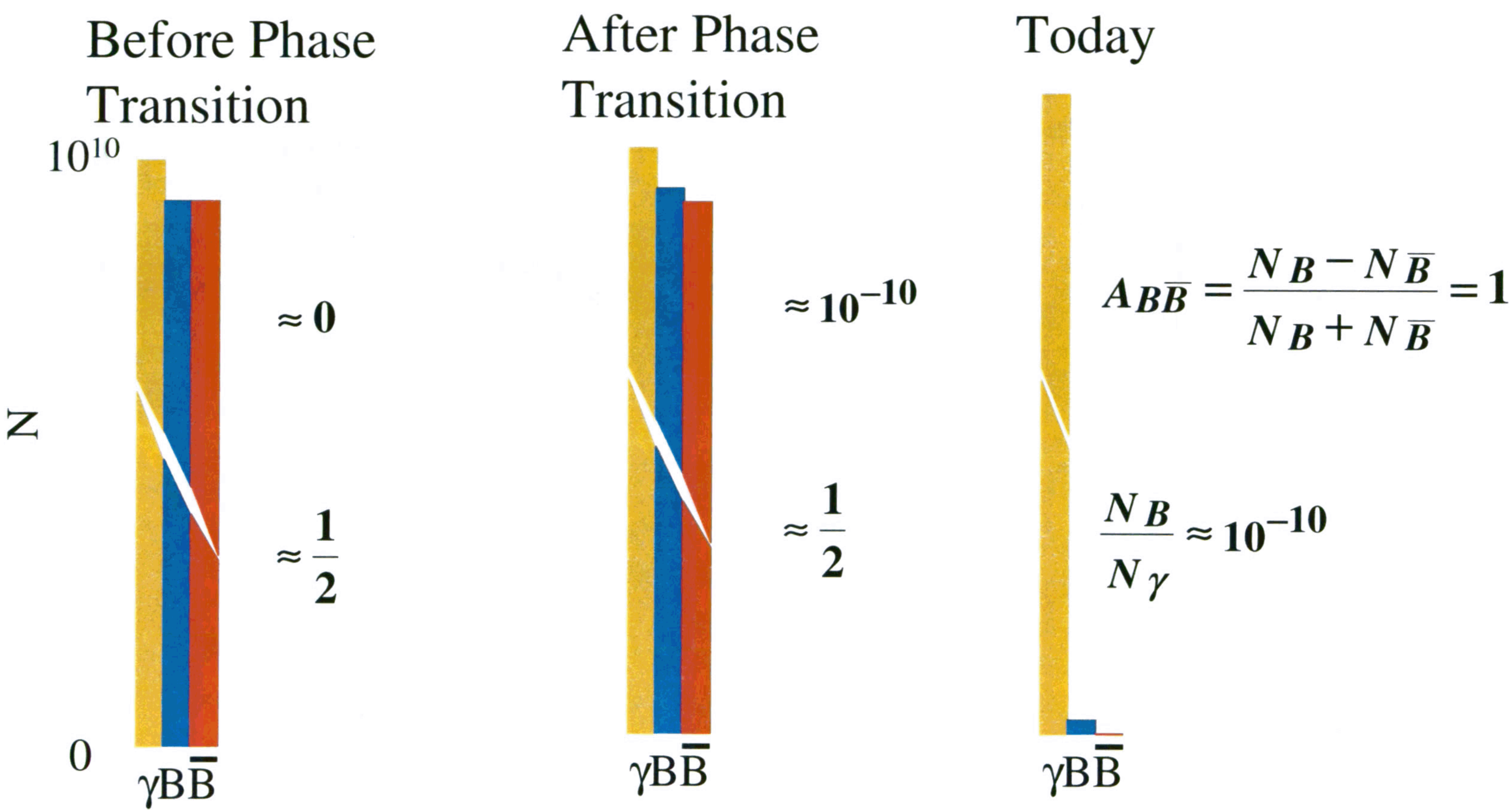
- Theory as distributions
- EDM rules out theories
- SM leaves room for discovery

- Strong CP
- SUSY GUT
- Electro-weak Baryogenesis



10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
B.R. ($\mu \to e\gamma$) in minimal SO(10)
0.6
0.8
1.0
1.2
1.4
The top Yukawa coupling at the GUT scale
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
B.R. ($\mu \to e$ in Ti) in minimal SO(10)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
EDM of neutron (e•cm)

B-$\overline{\text{B}}$ ASYMMETRY IN THE UNIVERSE



STATUS OF EDM MEASUREMENTS
(e-cm)

Fundamental Particles

n	ILL	$\lvert d_n \rvert$	$< 1.2 \times 10^{-25}$
	PNPI	$\lvert d_n \rvert$	$< 1.1 \times 10^{-25}$
	ILL (^{199}Hg)	$\lvert d_n \rvert$	$< 6(3) \times 10^{-26}$
	PSI	$\lvert d_n \rvert$	$< (1) \times 10^{-27}$
	LANSCE (^{3}He)	$\lvert d_n \rvert$	$< (2) \times 10^{-28}$
p		$\lvert d_p \rvert$	$< 10^{-22}$
Λ	$\Lambda \to p\pi^-$ assym.	$\lvert d_\Lambda \rvert$	$< 1.5 \times 10^{-16}$
e	g-2	$\lvert d_e \rvert$	$< 4 \times 10^{-16}$
ν	reactor exp.	$\lvert d_\nu F_3 \rvert$	$< 2 \times 10^{-20}$
μ	g-2	$\lvert d_\mu \rvert$	$< 1.1 \times 10^{-18}$
		$\lvert d_\mu \rvert$	$< 10^{-24}$
τ	$\Gamma(Z \to \tau^+\tau^-)$	$\lvert d_\tau \rvert$	$< 4.5 \times 10^{-18}$

Paramagnetic Atoms

H	Lamb shift		$\lvert d_e \rvert < 2 \times 10^{-13}$
Fe^{+3}	$d_{3/2}$		$\lvert d_e \rvert < 2 \times 10^{-22}$
Rb	5s	$\lvert d_a \rvert < 1.2 \times 10^{-23}$	$\lvert d_e \rvert < 5 \times 10^{-25}$
Cs	6s	$\lvert d_a \rvert < 1.3 \times 10^{-23}$	$\lvert d_e \rvert < 1 \times 10^{-25}$
Tl	$5p_{1/2}$	$\lvert d_a \rvert < 2(?) \times 10^{-24}$	$\lvert d_e \rvert < 4(?) \times 10^{-27}$

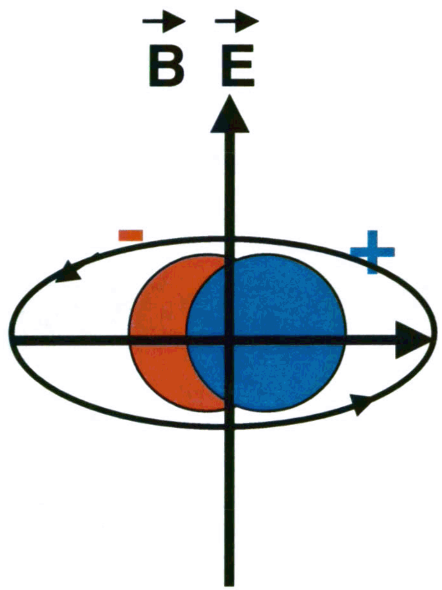
Diamagnetic Atoms

^{129}Xe	Wash.	$\lvert d_a \rvert < 2 \times 10^{-26}$	$\lvert d_n \rvert < 2 \times 10^{-23}$
^{199}Hg	Wash.	$\lvert d_a \rvert < 2(?) \times 10^{-28}$	$\lvert d_n \rvert < 2(?) \times 10^{-26}$

Polar Molecules

YF	$\lvert d_e \rvert < 10^{-28}$
PbO	$\lvert d_e \rvert < 10^{-30}$

THE BASIC TECHNIQUE



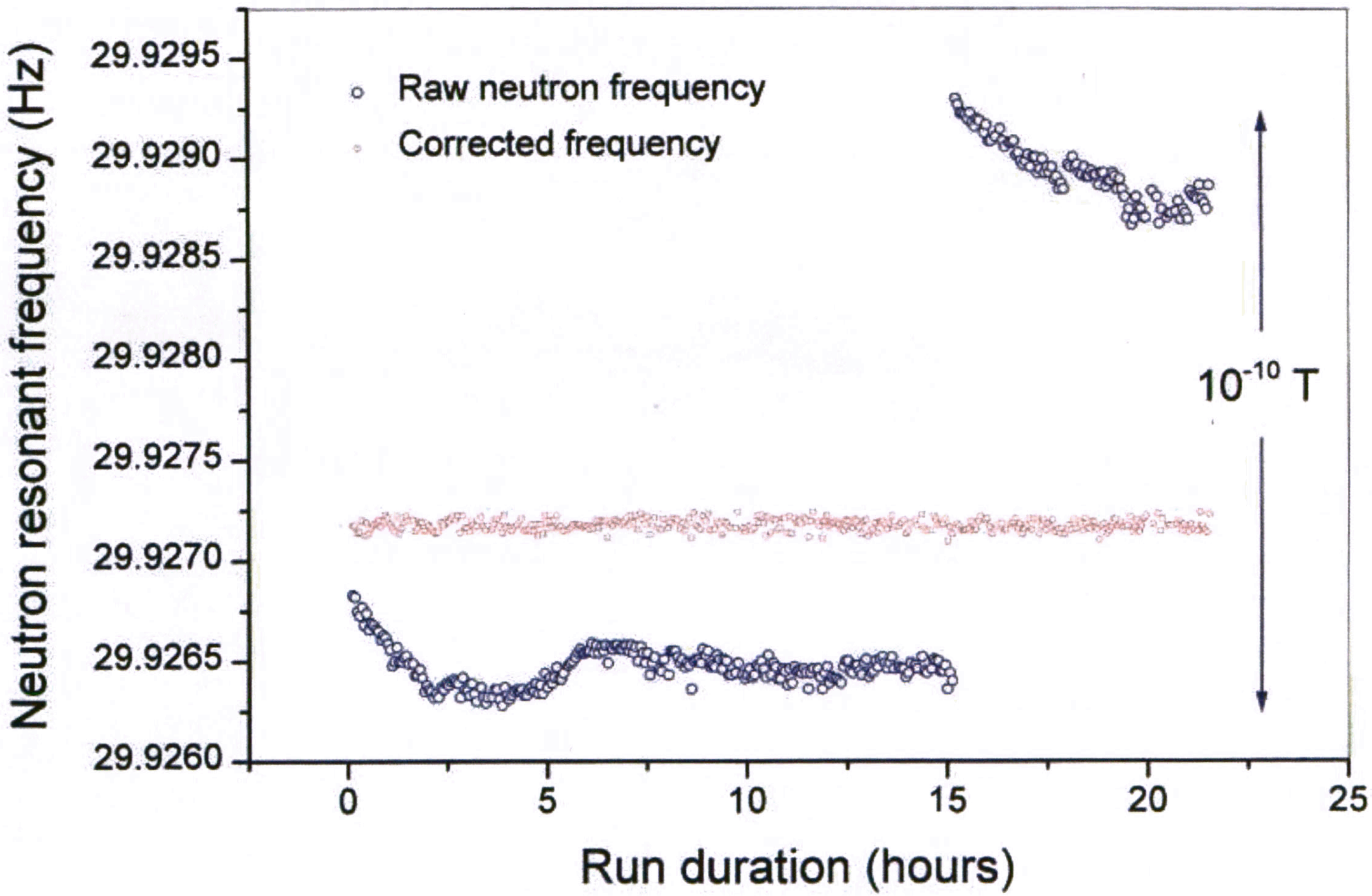
Look for a precession frequency ω_d

$s = 1/2$ dipole moment d_n

Figure of Merit for EDM Experiments ~ $E\sqrt{N\tau}$ $\longrightarrow$ **125**

$E \longrightarrow 5E$ $\quad \tau \longrightarrow 5\tau$ $\quad N \longrightarrow 125\ N$

Magnetic Field Drift Correction



^{3}He-DOPANT AS AN ANALYZER

$^3\vec{He} + \vec{n} \rightarrow t + p$ σ(parallel) $< 10^2$ b
σ(opposite) ~ 10^4 b

UCN loss rate ~
$1 - \vec{p}_3 \bullet \vec{p}_n = 1 - p_3 p_n \cos(\gamma_n - \gamma_3) B_0 t$
$|\gamma_n - \gamma_3| = |\gamma_n|/10$

^{3}He concentration must be adjusted to keep the lifetime τ reasonable for a given value of the ^{3}He polarization.

The proper value for the fractional concentration x = Atoms-^{3}He/Atoms-^{4}He ~ 10^{-10}.

^{4}He AS A DETECTOR

$$^3\vec{He} + \vec{n} \rightarrow t + p$$

t + p share 764 keV of kinetic energy. They scintillate while stopping in the ^{4}He. Light detected from the cell is a signature that the neutron had a polarization opposite to the ^{3}He.

The emitted light (~3 photons/keV) is in the XUV ~ 80 nm.

A wavelength shifter (TPB) is used to change it to the blue, where it can be reflected and detected. Getting the light out of a cryogenic system is a challenge.

The walls and the wavelength shifter must be made of materials that do not absorb neutrons or depolarize ^{3}He. For the neutrons, deuterated wavelength shifter and Ni will do; for the ^{3}He, ???

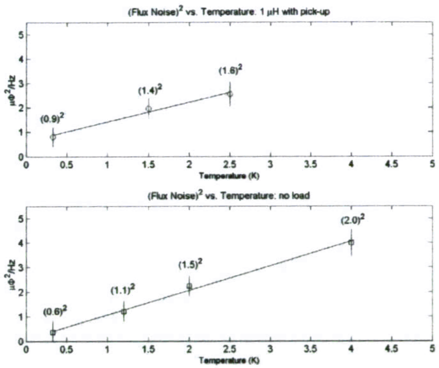
SQUIDs

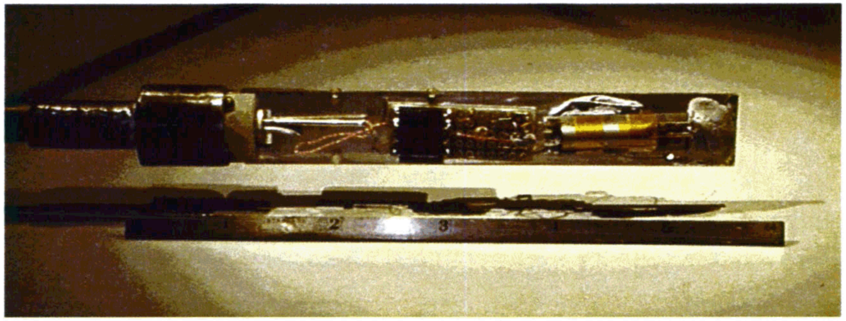
M. Espy, A. Matlachov

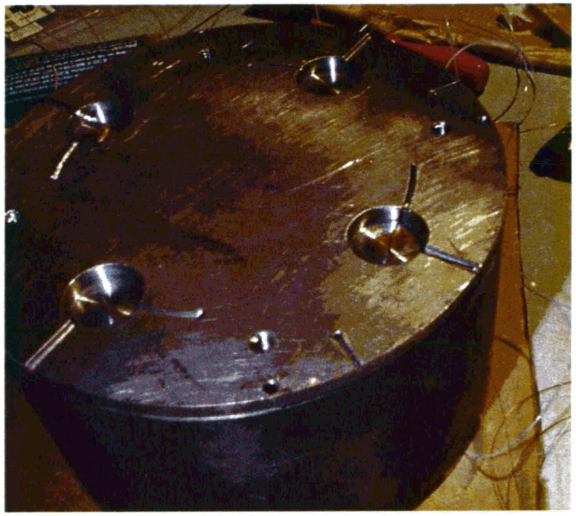
~100 cm^2 superconducting pickup coil

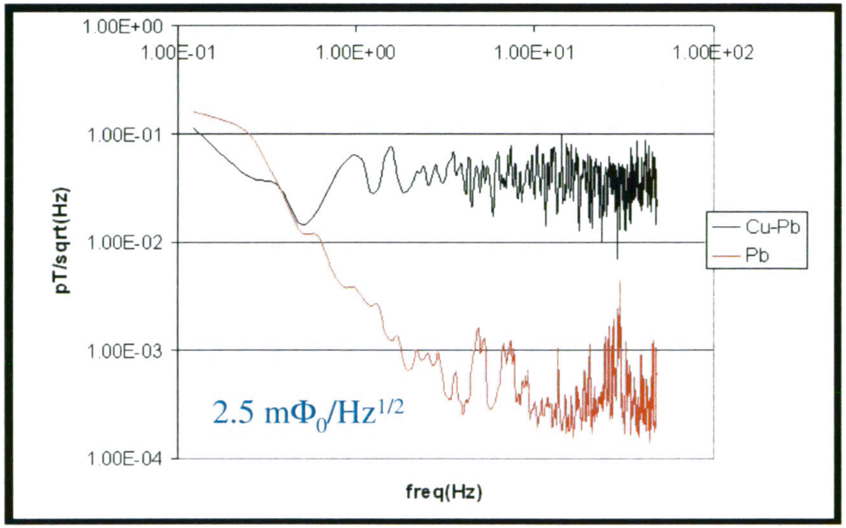
Flux = 2×10^{-16} Tm^2 = $0.1\ \Phi_0$

Noise = $4\ m\Phi_0/Hz^{1/2}$ at 10 Hz ~ $T^{1/2}$

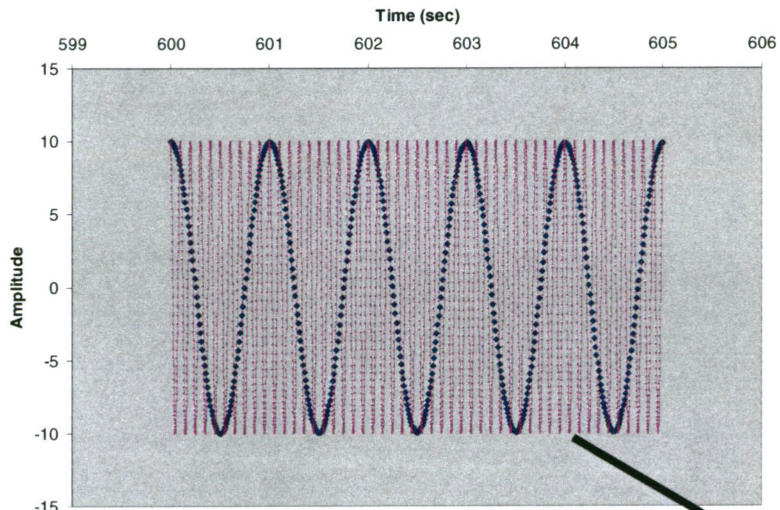


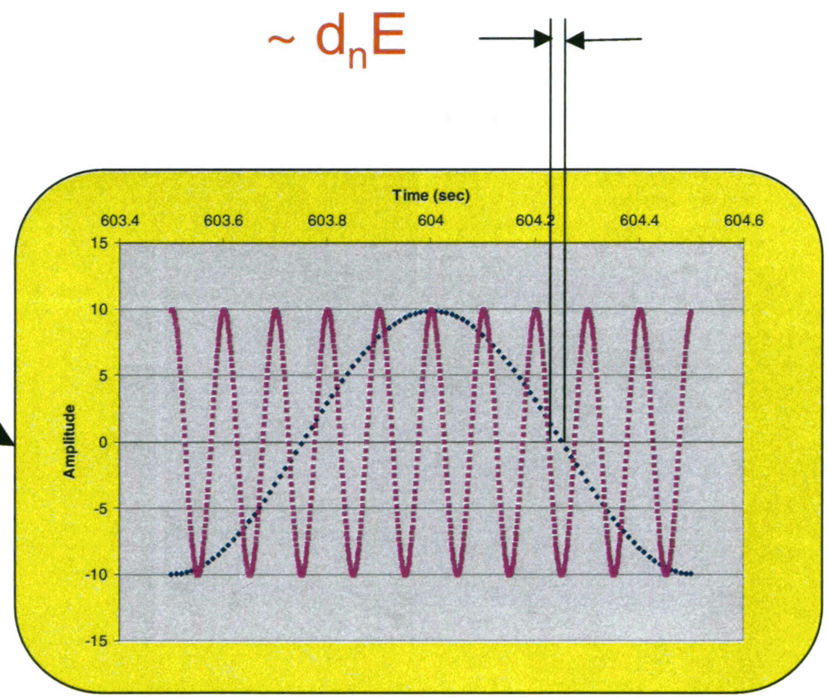






THE SIGNAL



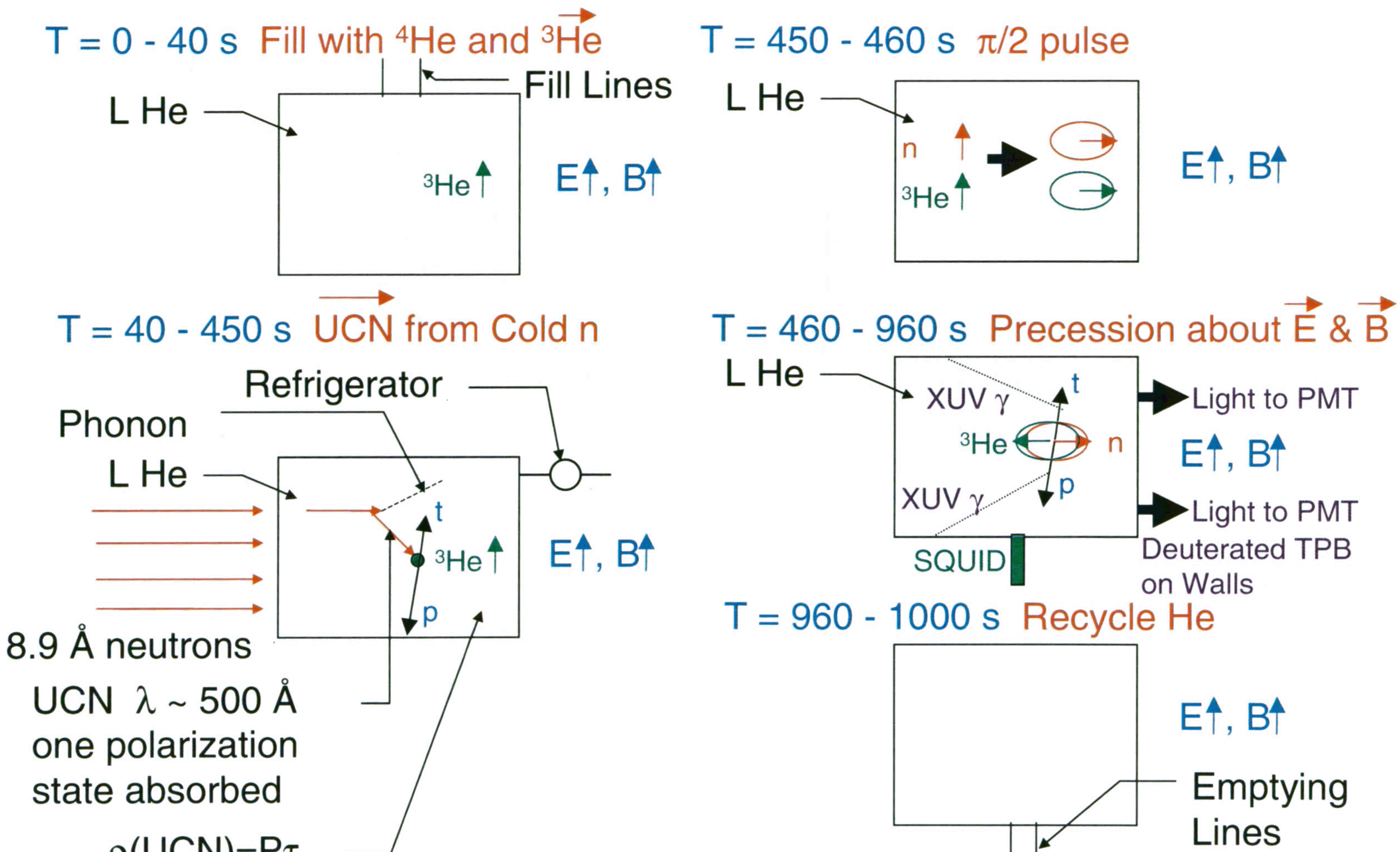


$^{3}He(n,p)t$ Scintillation Light

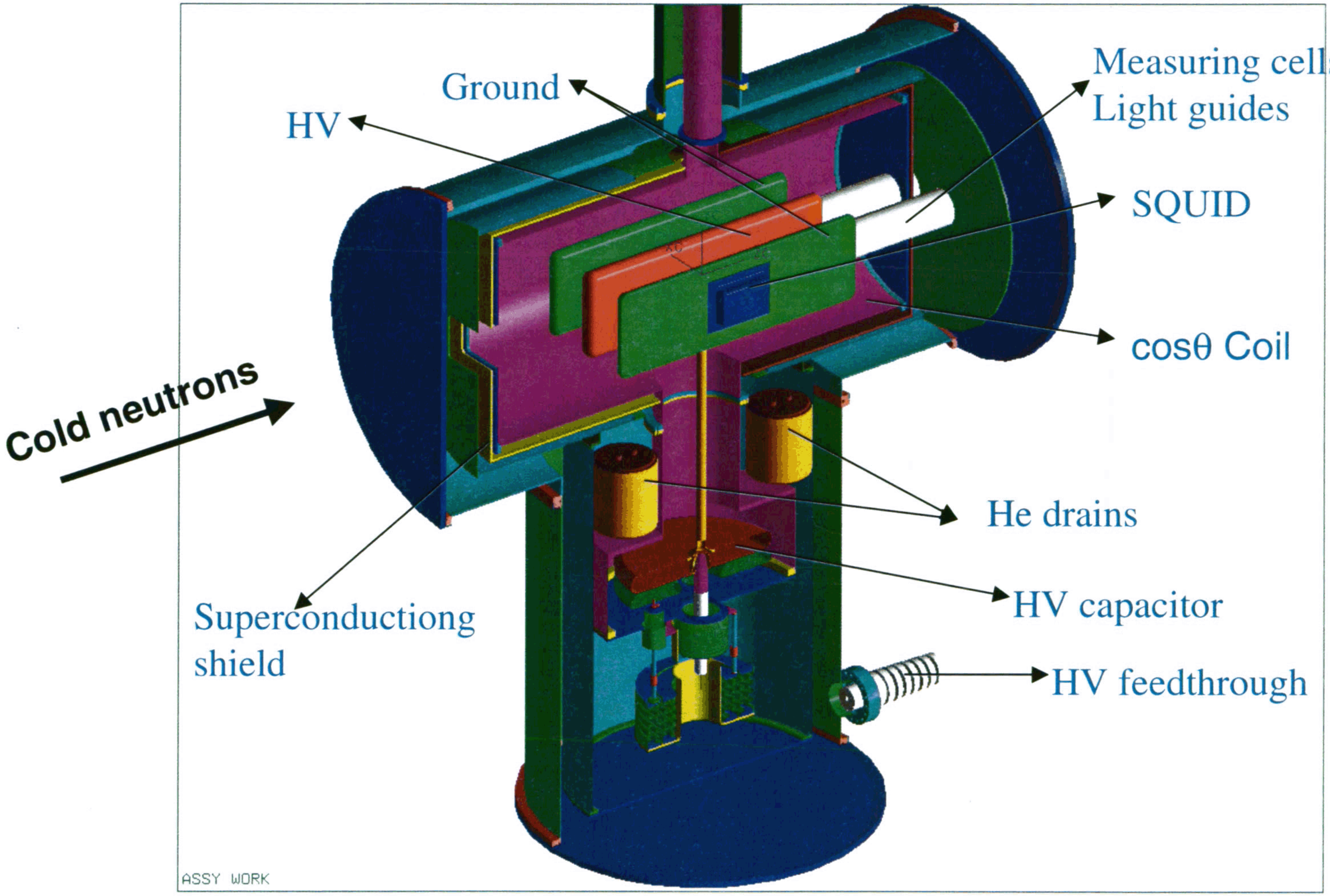
$\nu \sim (\gamma_3 - \gamma_n)$

SQUID $\nu \sim \gamma_3$

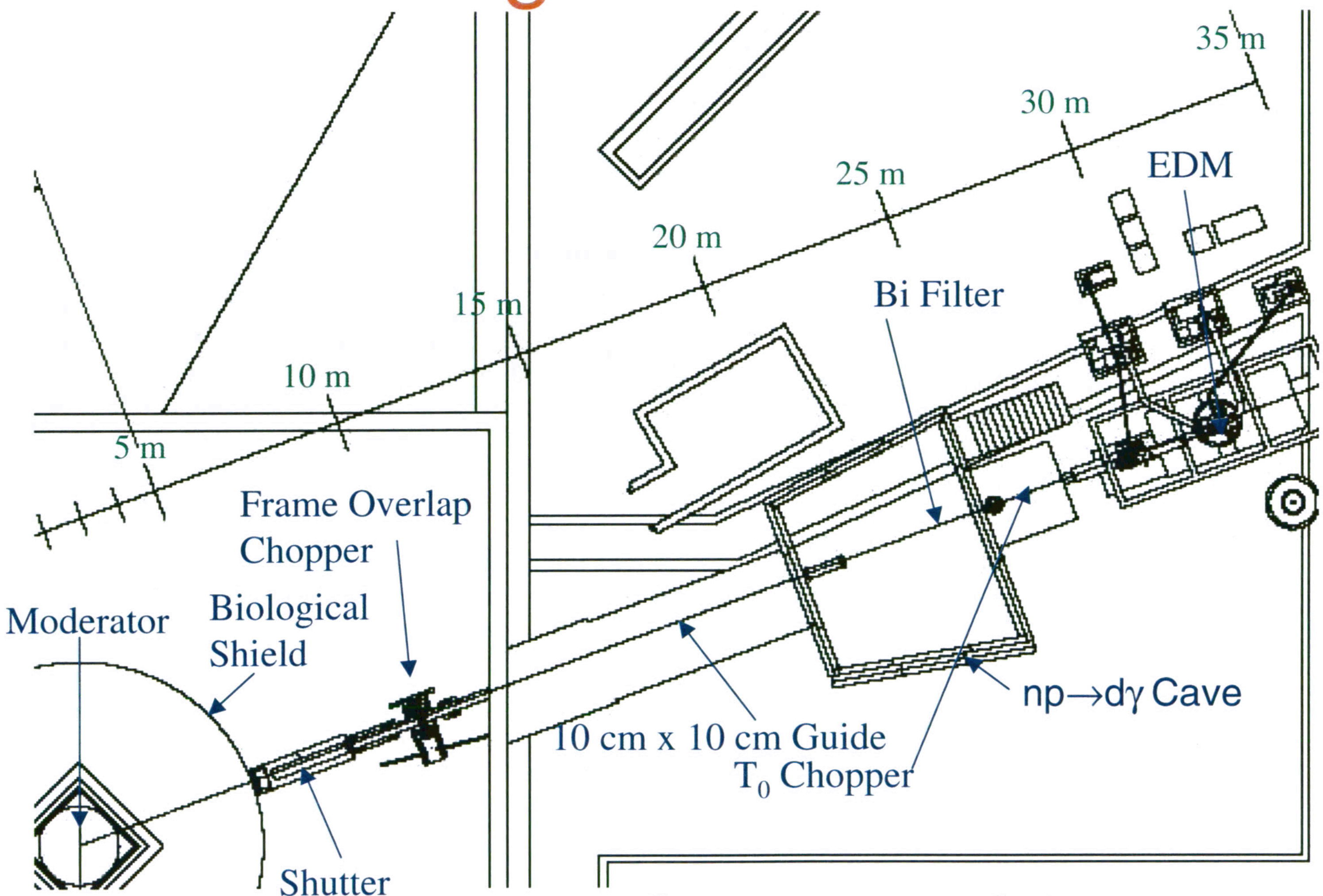
EXPERIMENT CYCLE



CONCEPTUAL DESIGN



Flight Path 12



ULTRACOLD NEUTRONS

Ultracold neutrons (UCN) have a low enough energy to be bottled. Their wavelength is long enough to feel a generally repulsive force (totally internally reflected) from certain materials as described by their Fermi potential. The minimum wavelength is material dependent; e.g. a good one is ^{58}Ni.

Properties:

$U_F \sim 200$ neV	$v \sim 5$ m/s	$\lambda \sim 500$ Å
$mg \sim 100$ neV/m		$\mu \sim 60$ neV/T

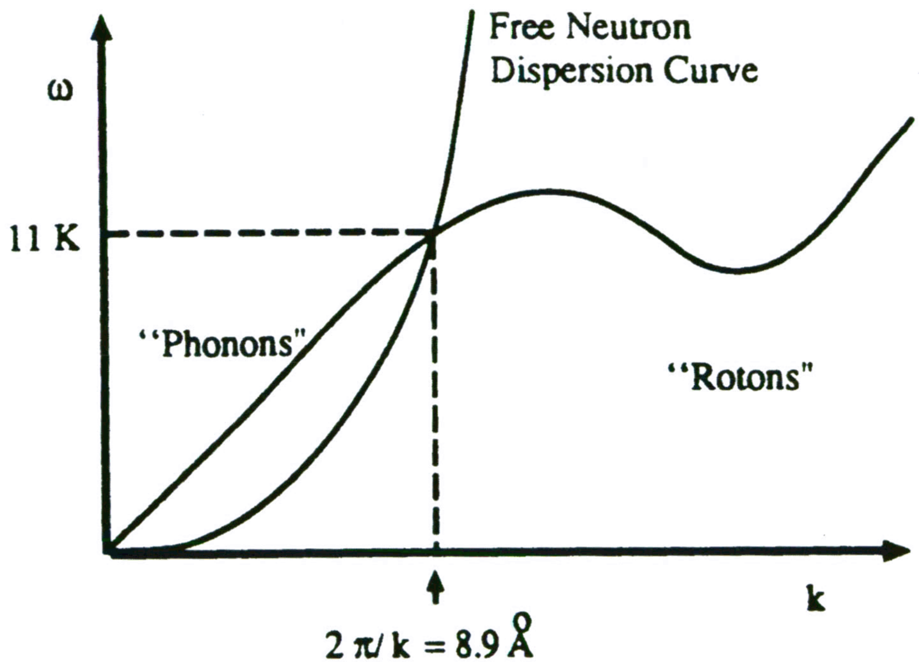
UCN can be bottled by

- materials
- the gravitational potential
- a gradient magnetic field

UCN can be polarized by

- magnetic fields
- gradient magnetic fields
- ^{3}He

SUPERTHERMAL SOURCE OF UCNs

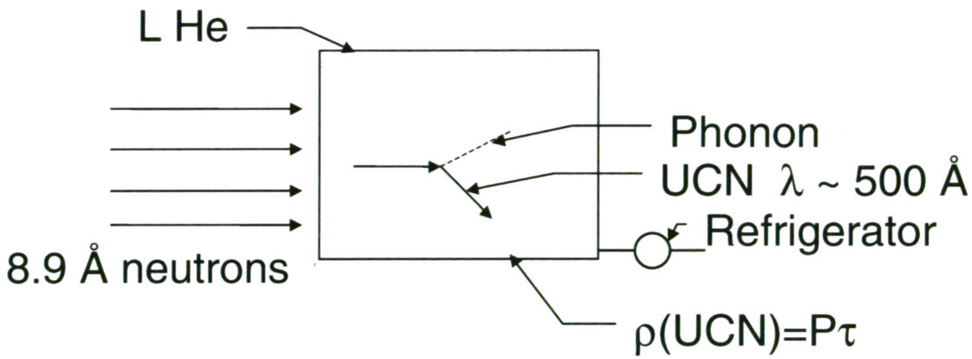


U_w = 200 neV
U_{LHe} = 20 neV

Quasi two-level system with single phonon upscattering suppressed by a large Boltzman factor.

$\tau_{up} \sim 100\ T^{-7}$ from 2-phonon upscattering

SUPERTHERMAL SOURCE OF UCNs



$$P = 7.2 \frac{d^2\Phi}{d\lambda d\Omega} \frac{1}{\lambda_w^3} \delta\Omega$$

Verified by NIST n-lifetime experiment!

LANSCE cold source $\Phi = 2 \times 10^{12}$ n/cm^2-s-sr

10-cm x 10-cm supermirror guide, $\delta\Omega = 0.01$ str.

$P = 1$ UCN/cm^3-s $\qquad\qquad$ $\tau \sim 500$ s

$\rho_{UCN} \sim 500$/cm^3 $\qquad$ (80 times lower than possible)

125 times current ILL UCN density.

Cell volume is 4000 cm^3 in each of two cells.

Velocity selection an advantage of a pulsed source

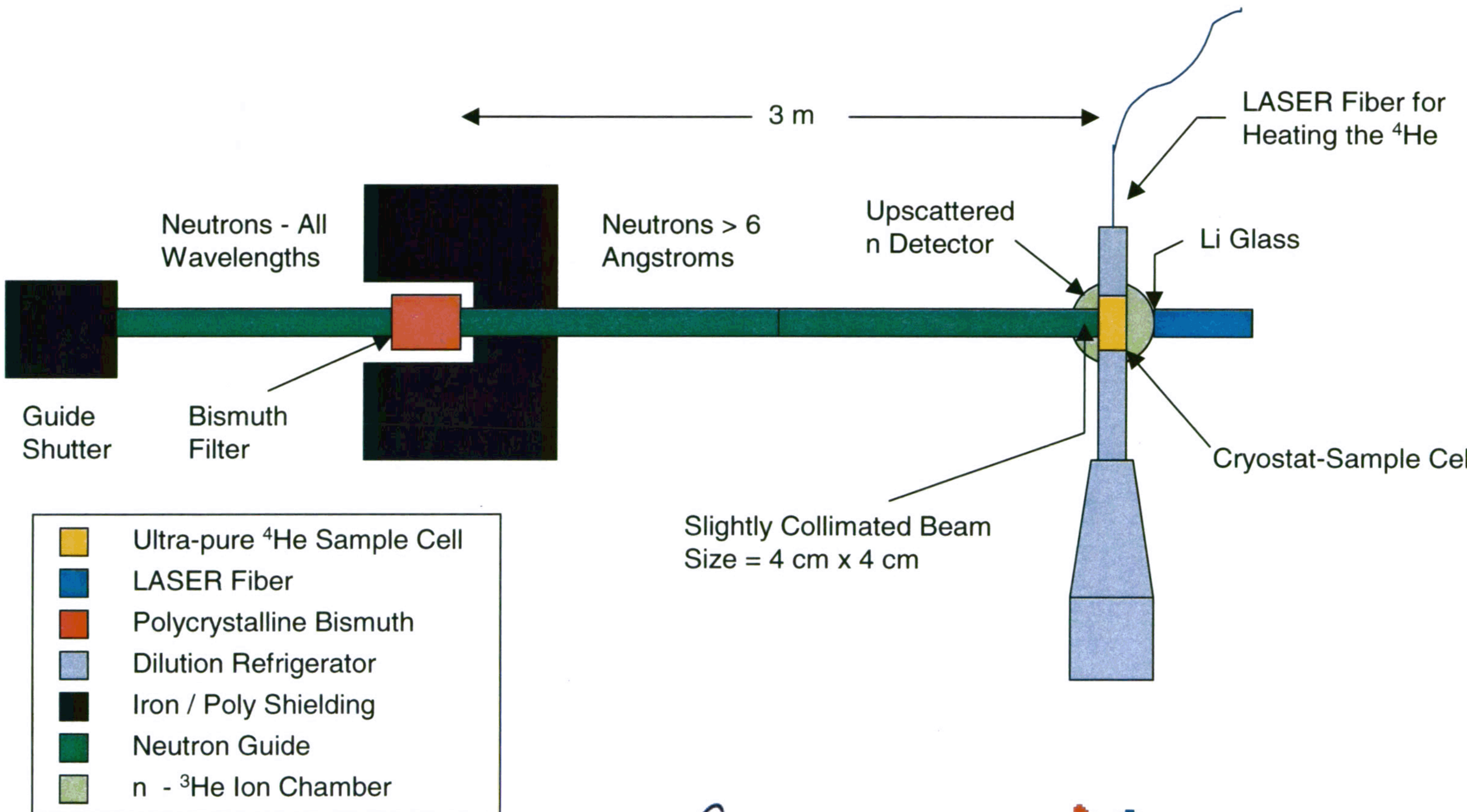
LIFETIME τ IN A BOTTLE

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_w} + \frac{1}{\tau_3} + \frac{1}{\tau_{up}}$$

where τ_n is the neutron lifetime,
τ_w is the wall lifetime,
τ_3 is absorption lifetime,
τ_{up} is upscattering lifetime.

PMT

EXPERIMENTAL LAYOUT
LANSCE FP 11a



10/28/02

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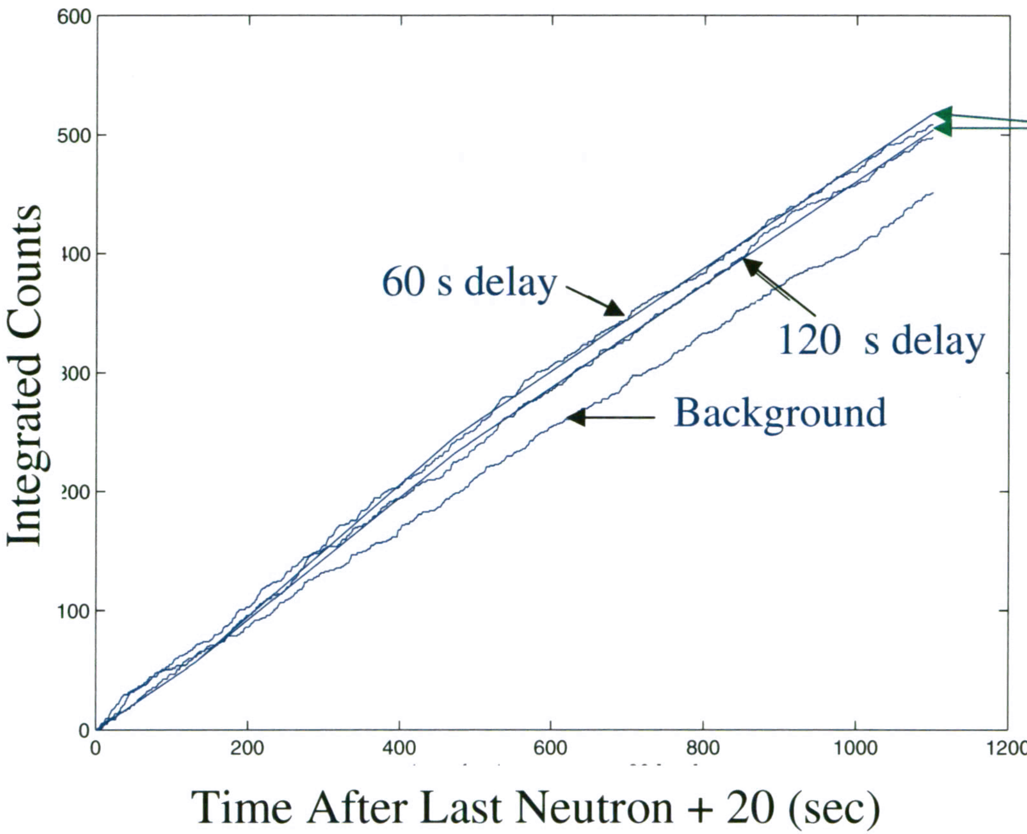
Physics Division / P25

UPSCATTERED NEUTRONS

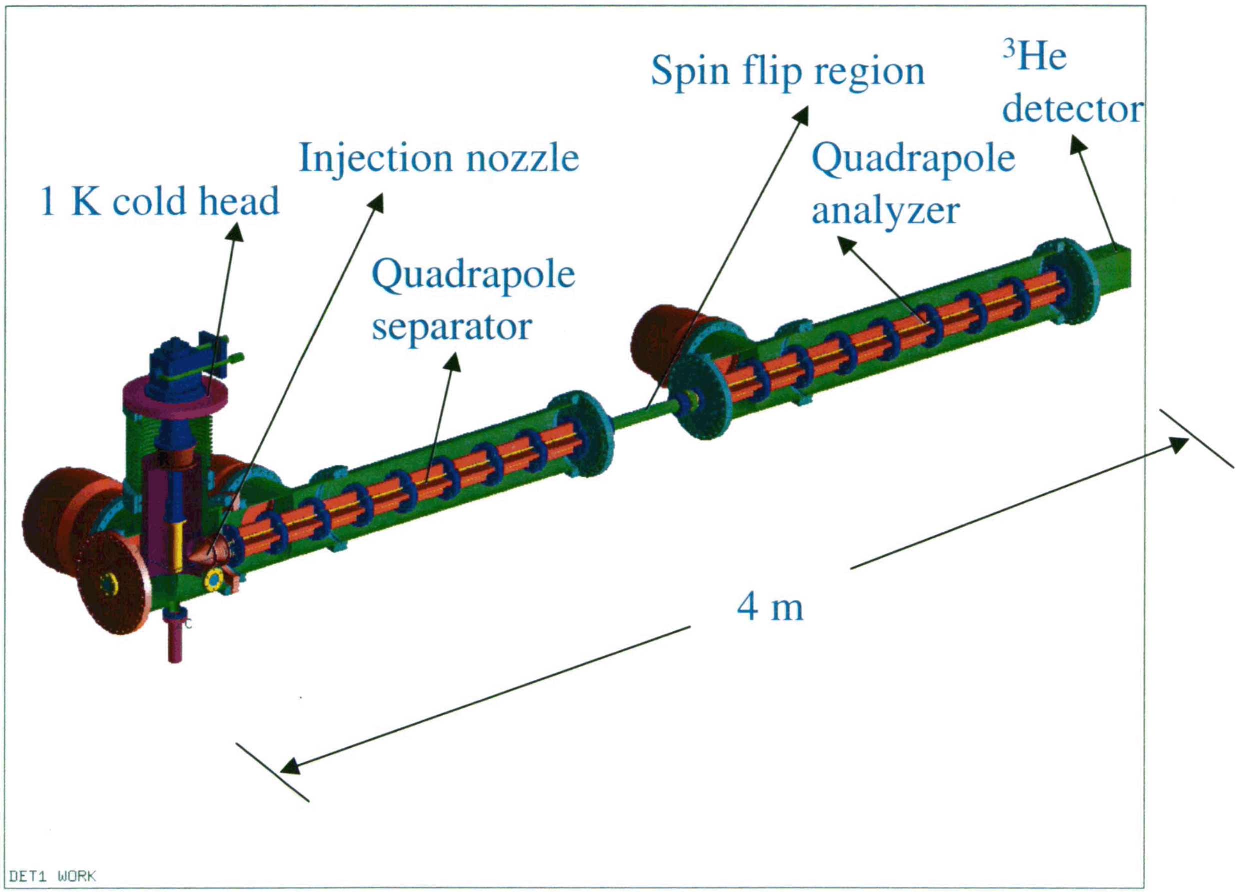


τ ~ 180 s

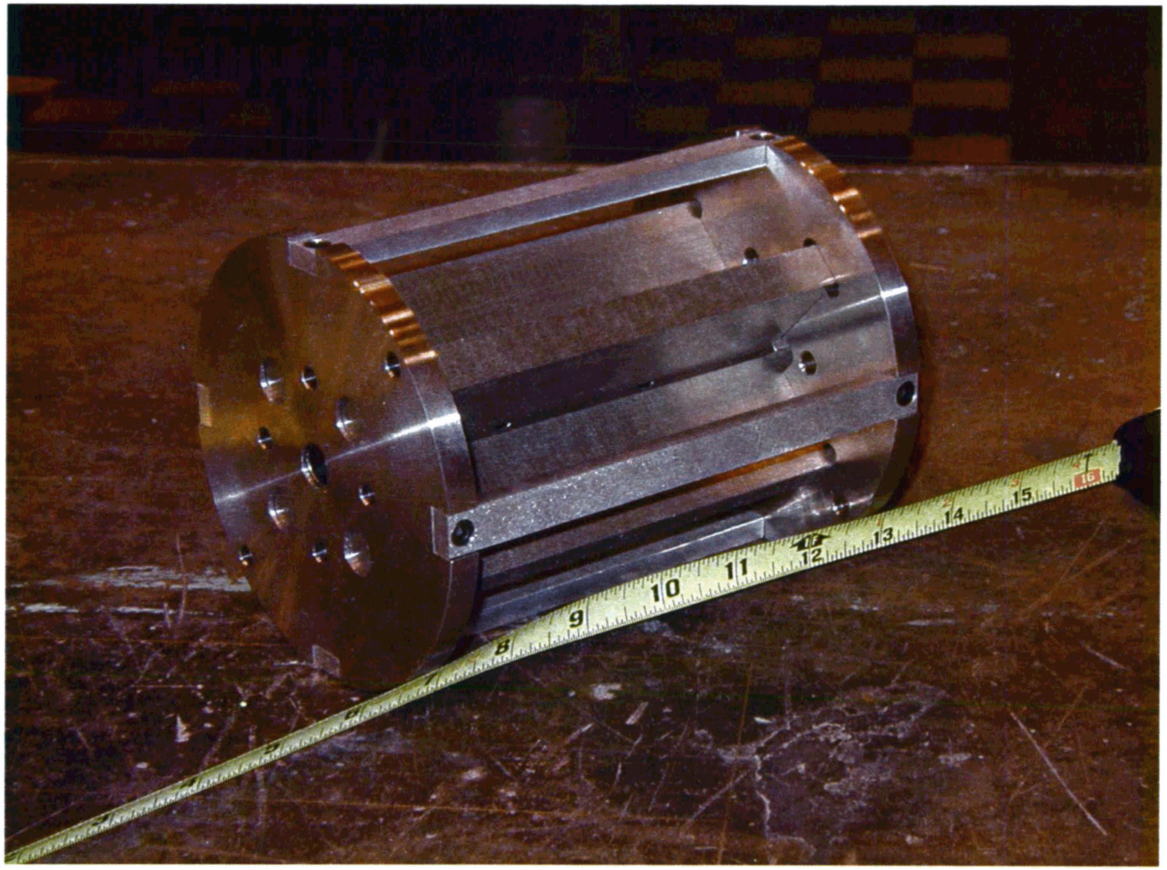
$$\int_0^t dt' N_0 e^{-t'/\tau} = N_0 \tau (1 - e^{t/\tau})$$

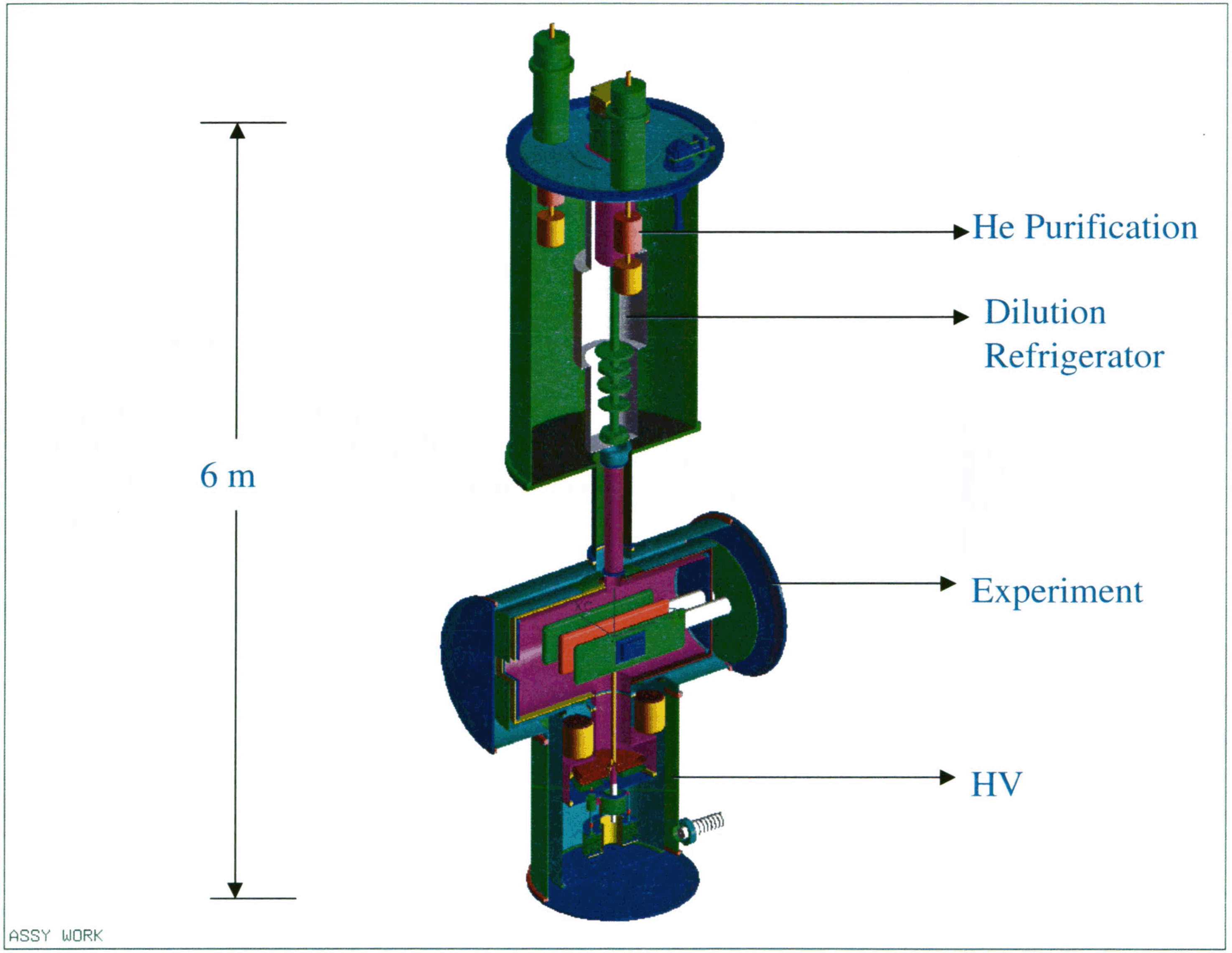
$N_0\tau$ consistent with production prediction and hole + β decay lifetimes

POLARIZED ^{3}He SOURCE



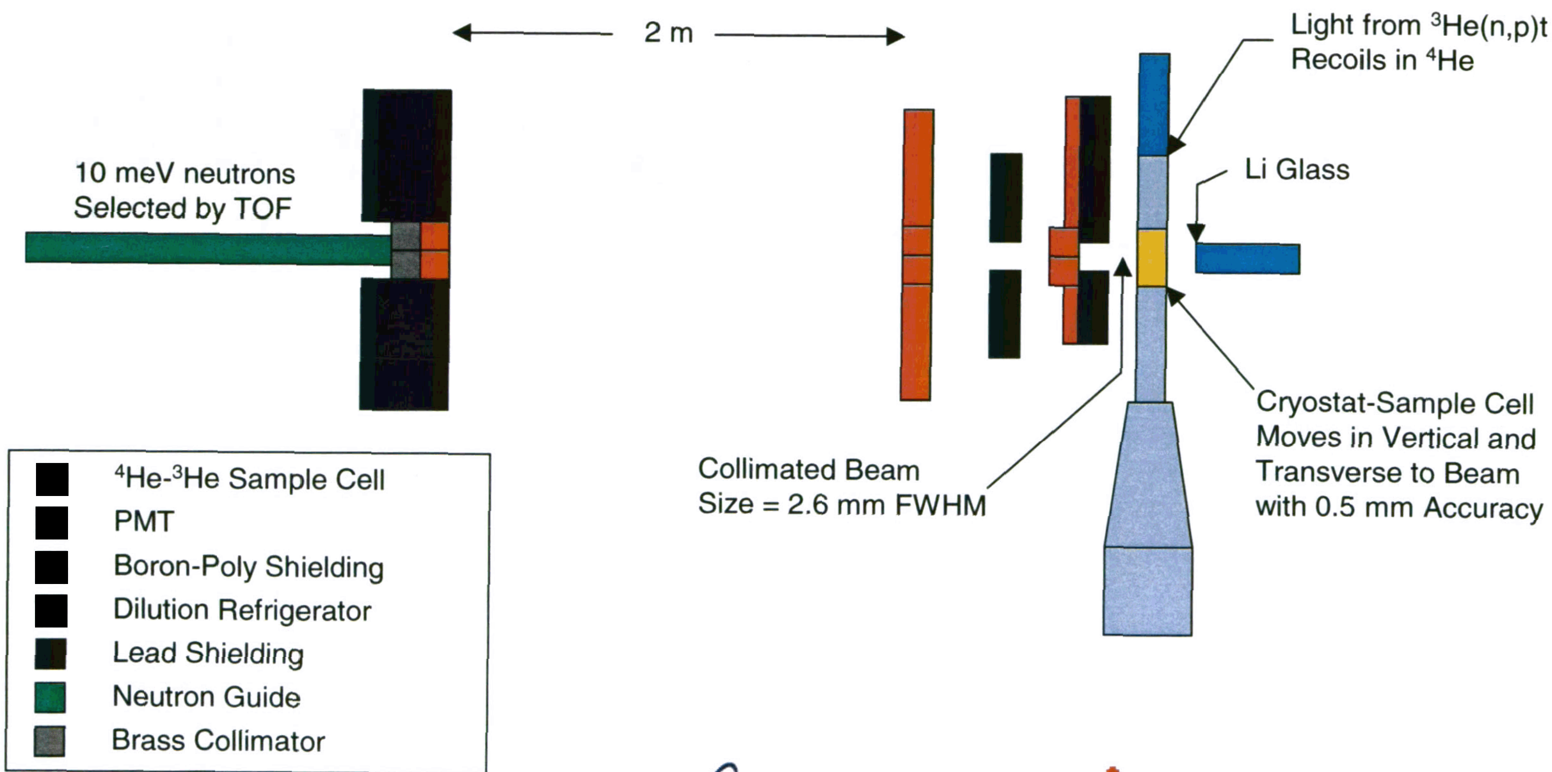
POLARIZER QUADRAPOLE




6 m
He Purification
Dilution
Refrigerator
Experiment
HV
ASSY WORK

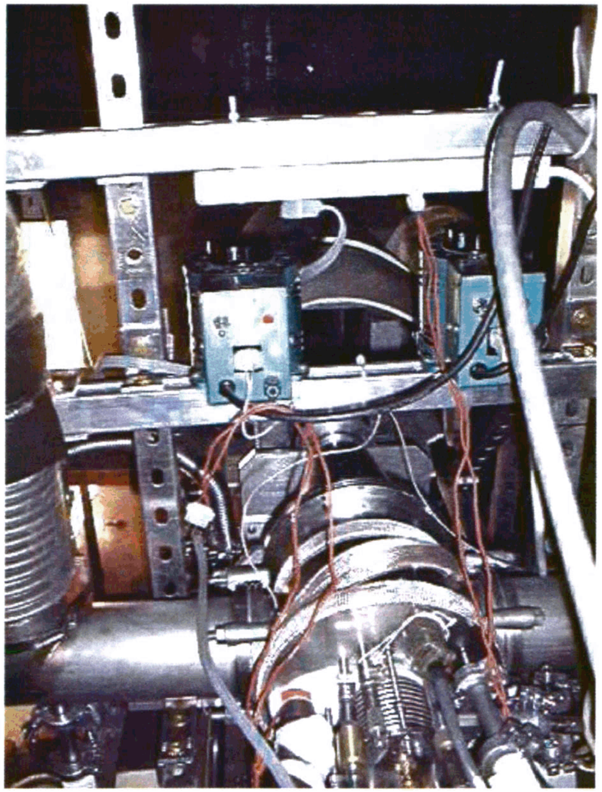
PMT

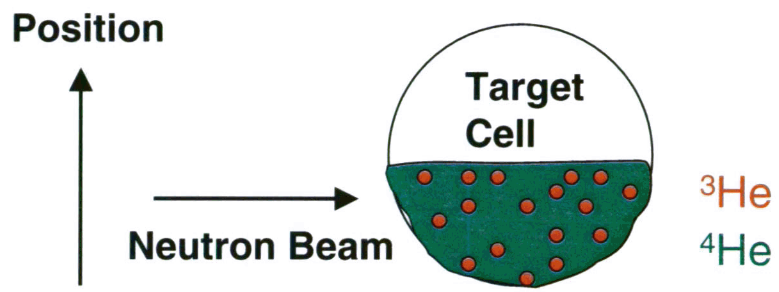
EXPERIMENTAL LAYOUT
LANSCE FP 11a

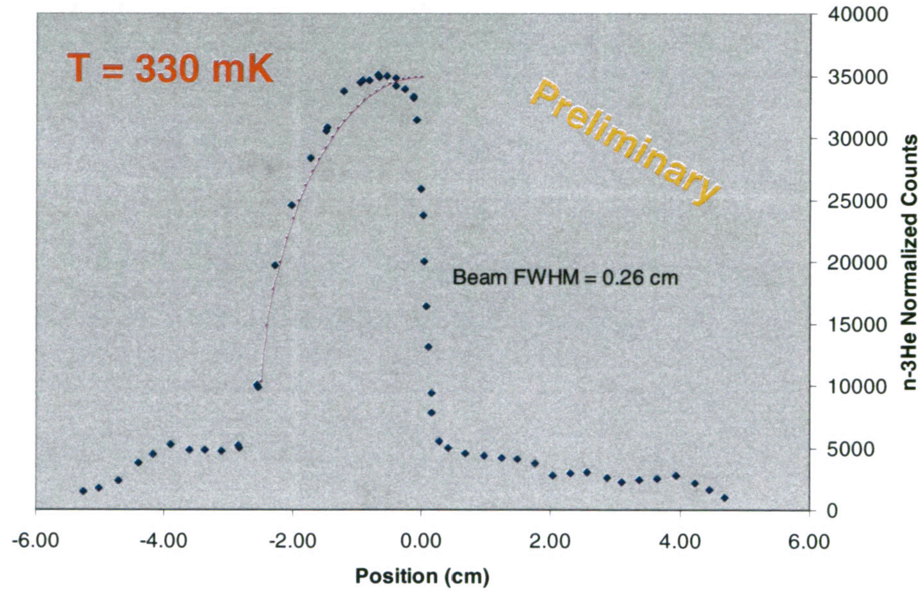


^{3}He Distributions in Superfluid ^{4}He

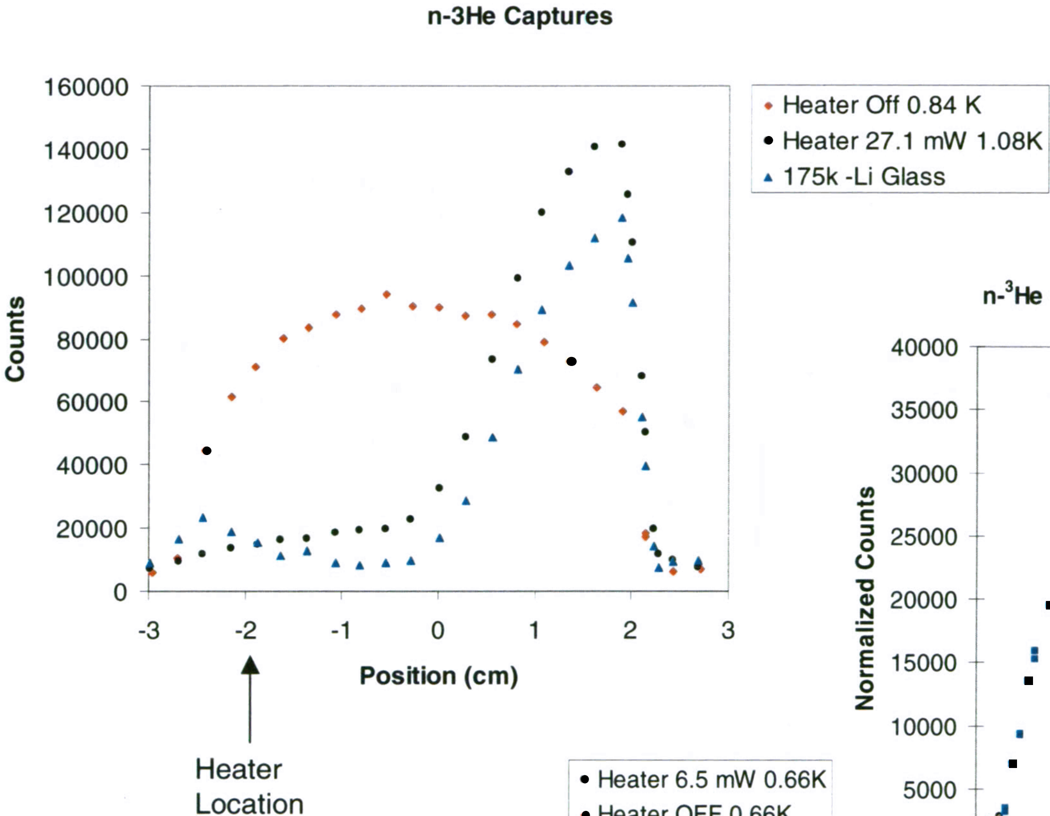
Dilution Refrigerator at LANSCE Flight Path 11a

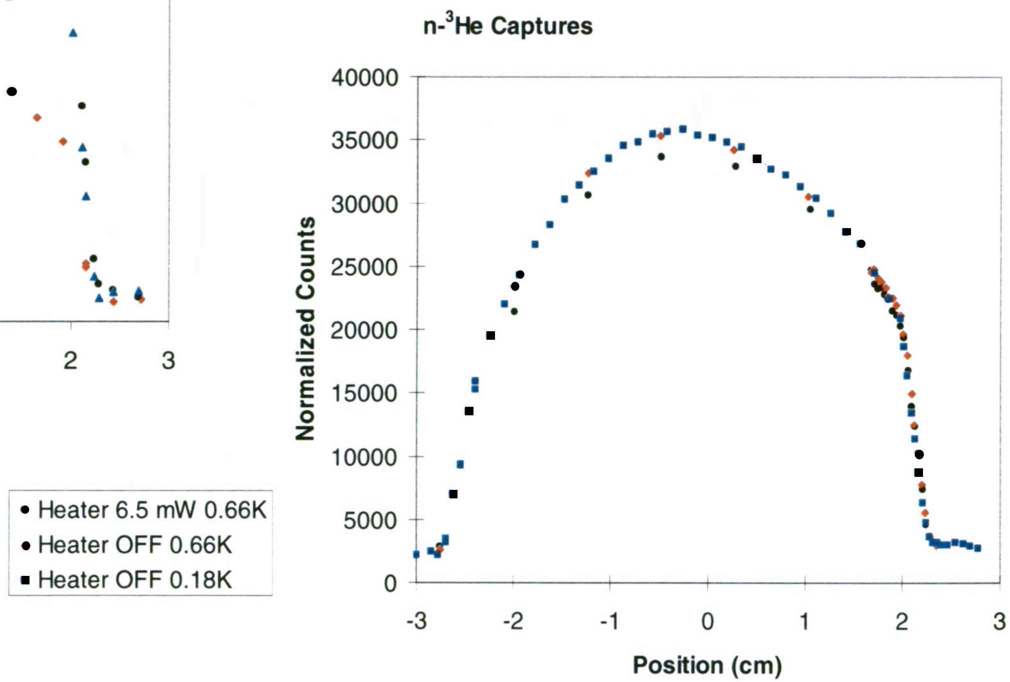






HEAT EFFECTS





DIFFUSSION COEFFICIENT

Three component Liquid: Superfluid ^{4}He, normal ^{4}He, concentration X of ^{3}He

Conservation of entropy: $\frac{\partial \rho s}{\partial t} = -\vec{\nabla} \bullet \rho s \vec{v}_n = 0$ in the steady state.

$\vec{\nabla} \bullet \vec{v}_n = 0 \Rightarrow \vec{v}_n = -\vec{\nabla}\Phi$ and Φ satisfies Laplace's equation $\nabla^2\Phi = 0$

The combination of normal flow that carries the ^{3}He and diffusions is

$$X\vec{v}_n - D\vec{\nabla}X = 0$$

Thus $\frac{1}{D}\vec{\nabla}\Phi = \frac{1}{X}\vec{\nabla}X = -\vec{\nabla}\log(X)$ and $\boxed{X = X_0 e^{-\Phi/D}}$

The heat flow is given by $\vec{q} = \rho s T \vec{v}_n$

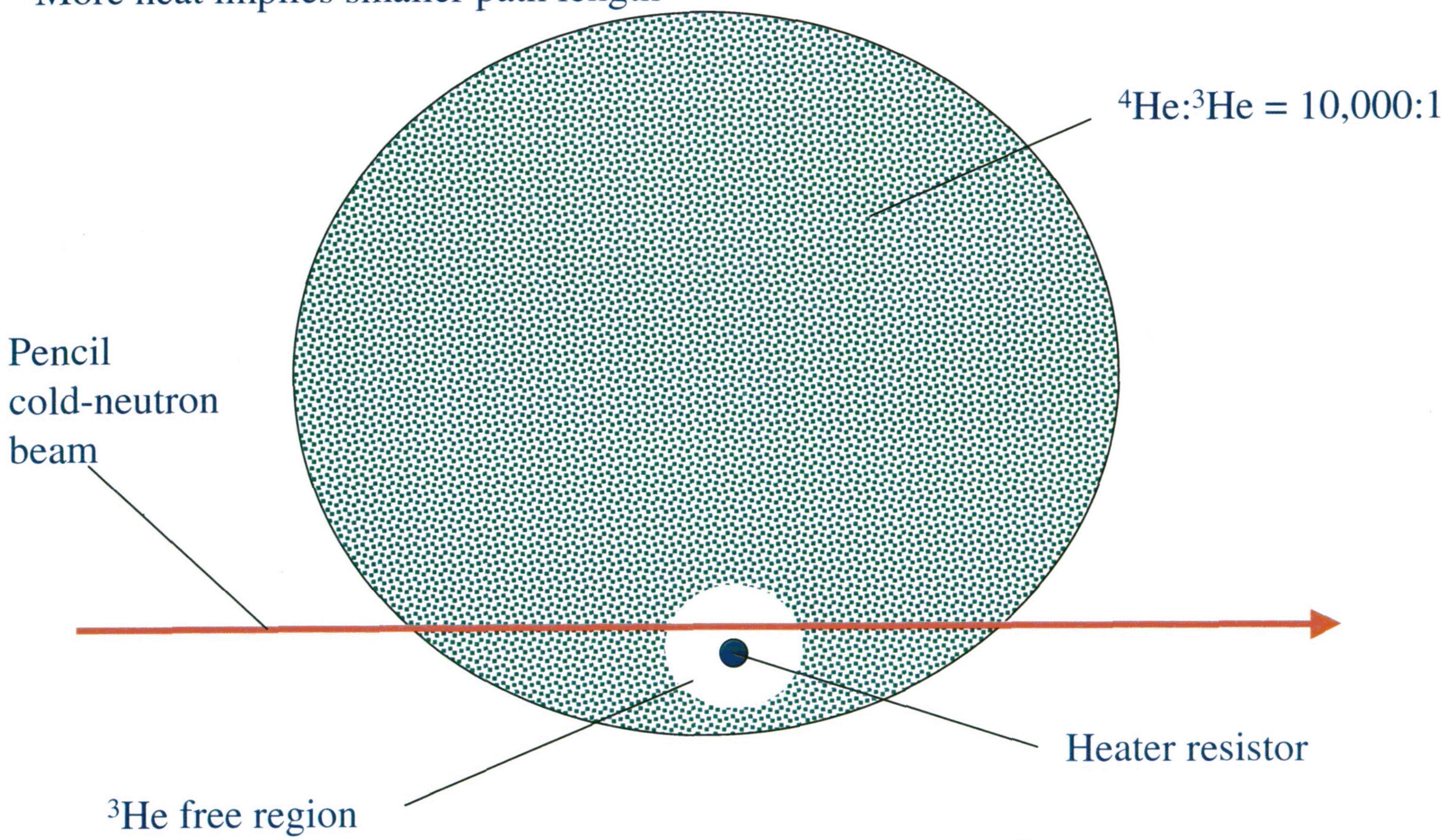
For a point heat source in the middle of a sphere

$$q(r) = \frac{P}{4\pi r^2} \Rightarrow v(r) = \frac{q(r)}{\rho s T} \Rightarrow \Phi(r) = \frac{P}{4\pi\rho s T}\frac{1}{r} \Rightarrow \boxed{X(r) = X_0 e^{-P/4\pi\rho s T D r}}$$

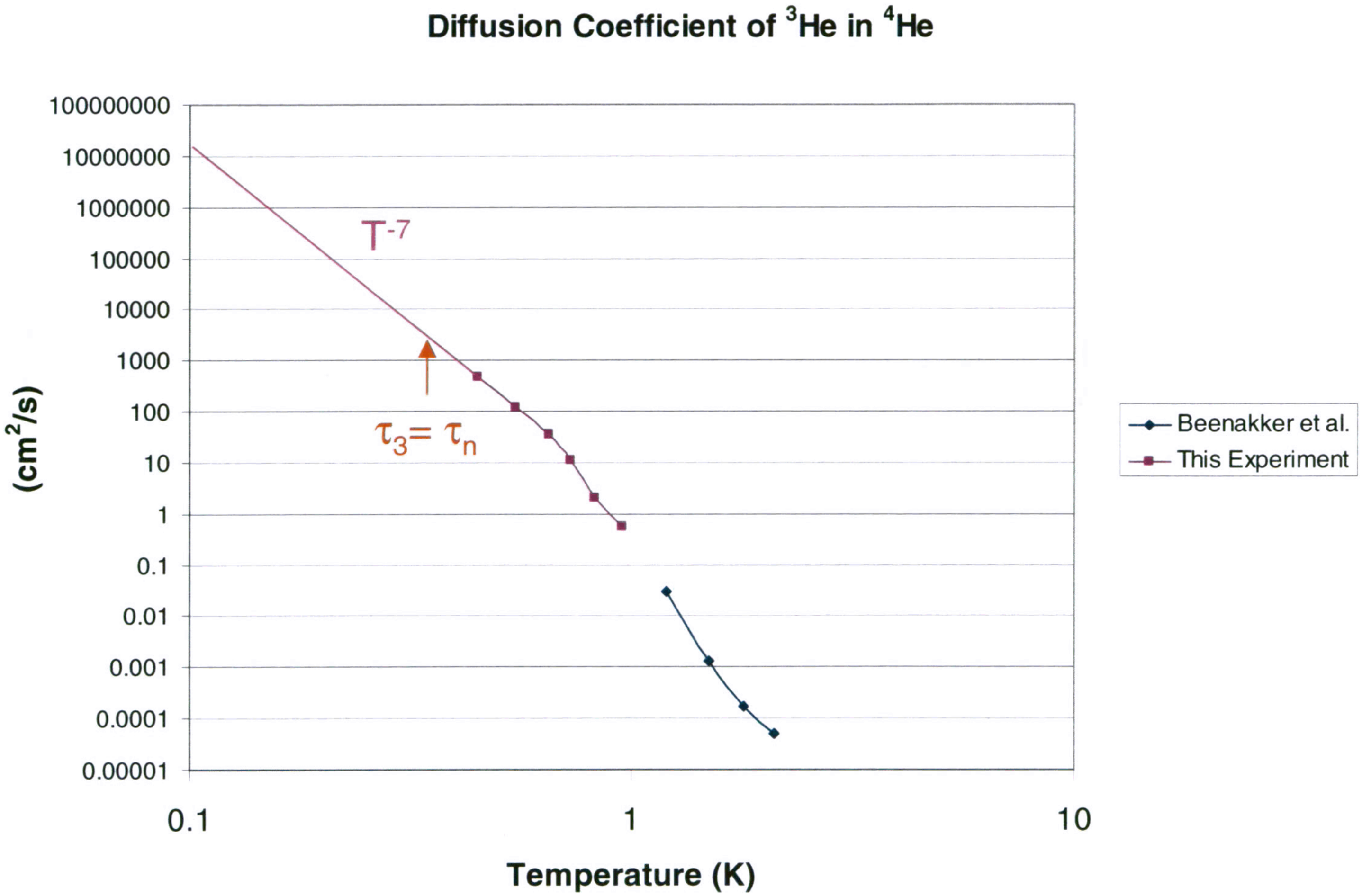
Diffusion time τ over a distance L is $\boxed{\tau = L^2/2D}$

DIFFUSION COEFFICENT

- $^3He(n,p)t$ measures path length of ^3He from scintillations from stopping p and t
- More heat implies smaller path length

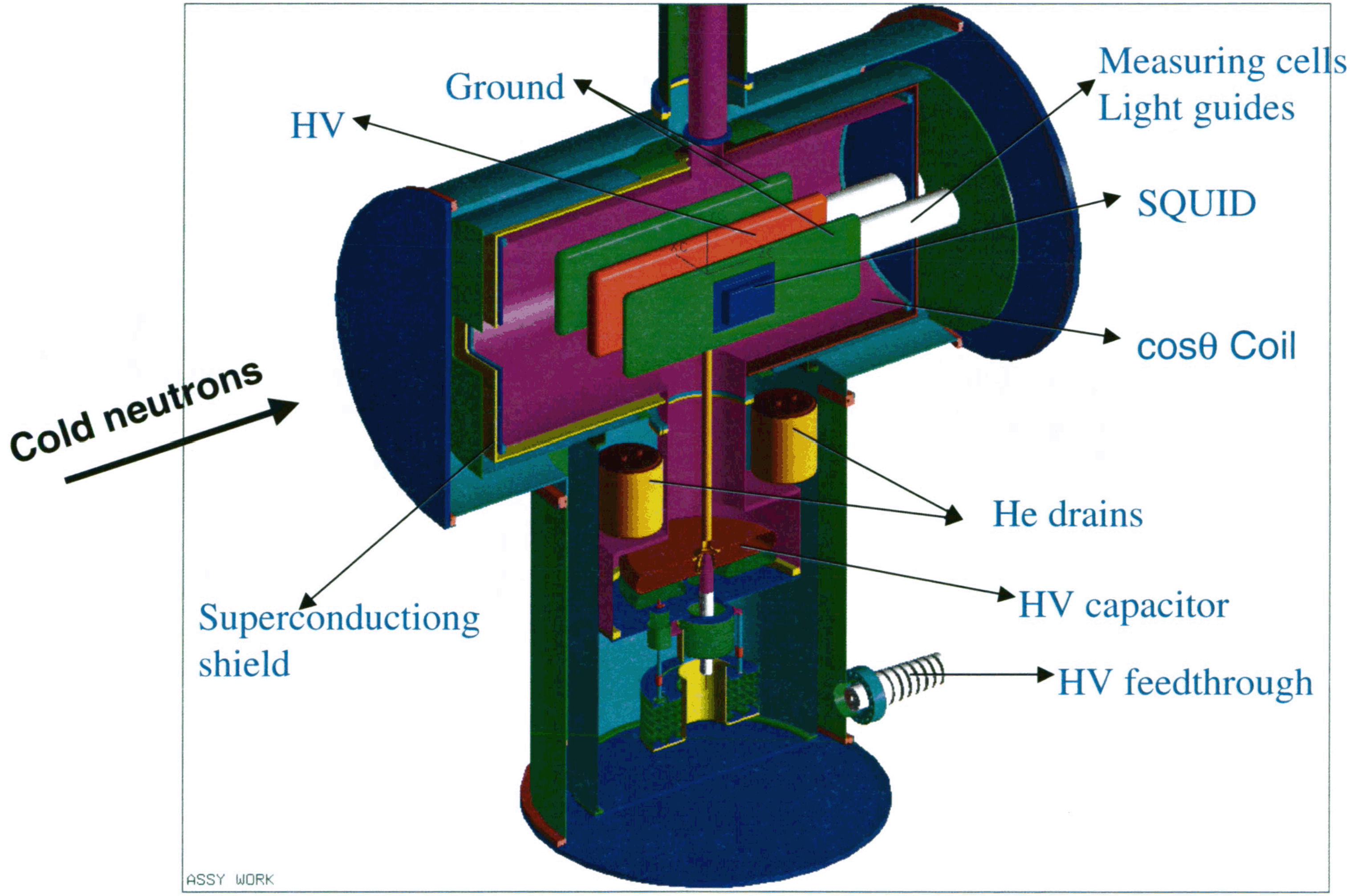


RESULTS



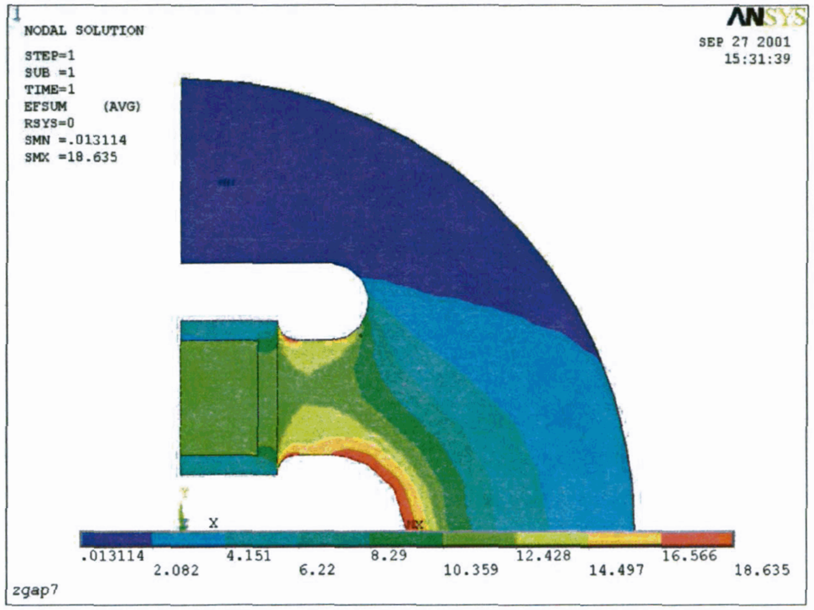
Diffusion Coefficient of 3He in 4He
100000000
10000000
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
(cm2/s)
T-7
τ3= τn
0.1
1
10
Temperature (K)
Beenakker et al.
This Experiment

CONCEPTUAL DESIGN



ELECTRIC FIELD CALCULATIONS

Ground plate	25 x 75 x 5 cm
HV plate	30 x 80 x 10 cm
Ground shell coil	30 cm radius



Uniformity in cell:

- 0.1% without side walls
- 1% with recess

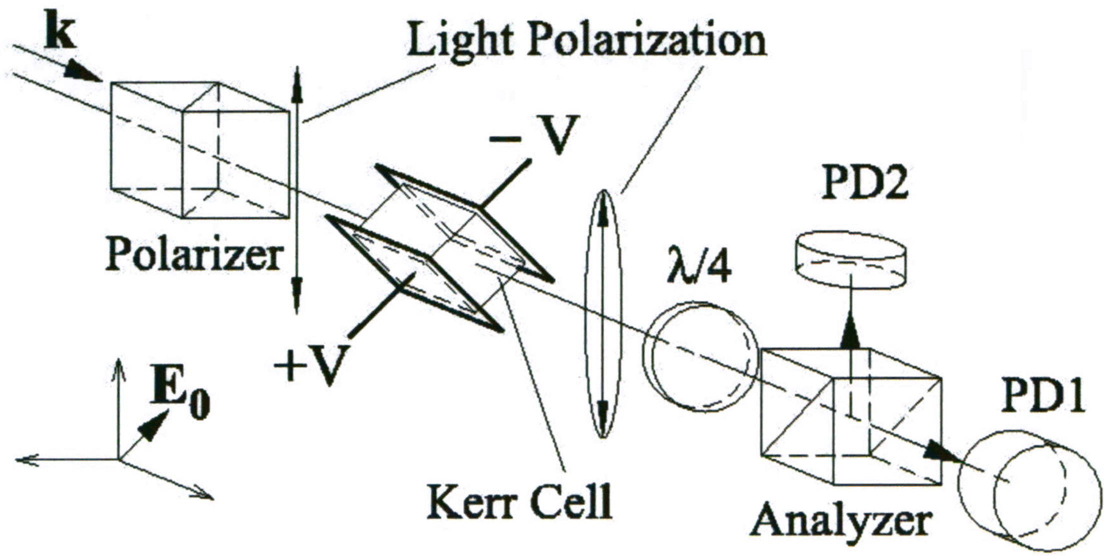
Peak E field is ~1.5 of value in cell

Next step - 3D model

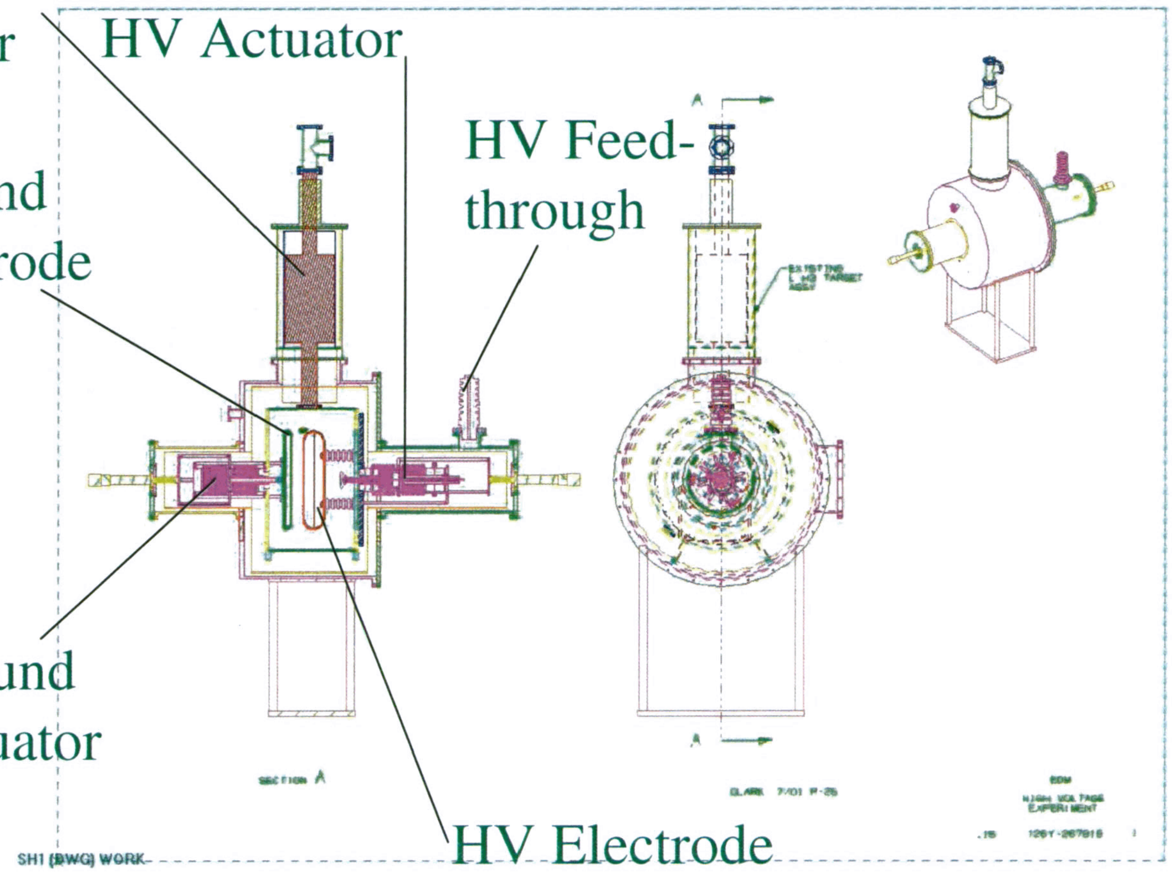
Cell 7.5 x 10 x 50 cm and 1.3 cm walls

ELECTRIC FIELD MEASUREMENT

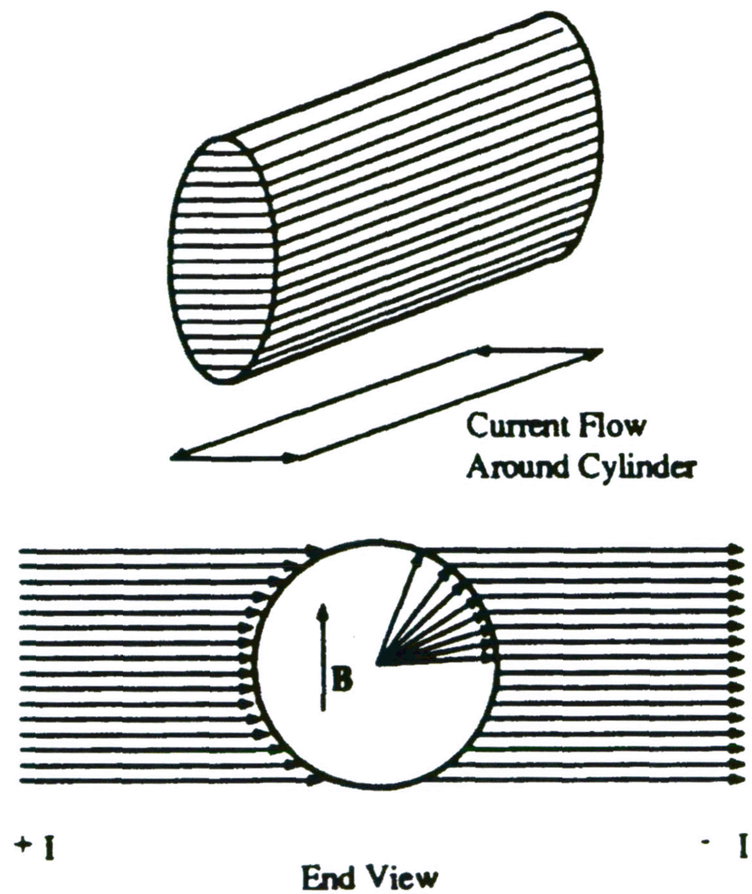
Kerr Effect $\varepsilon = \pi K l E_0^2$



ELECTRIC FIELD TEST



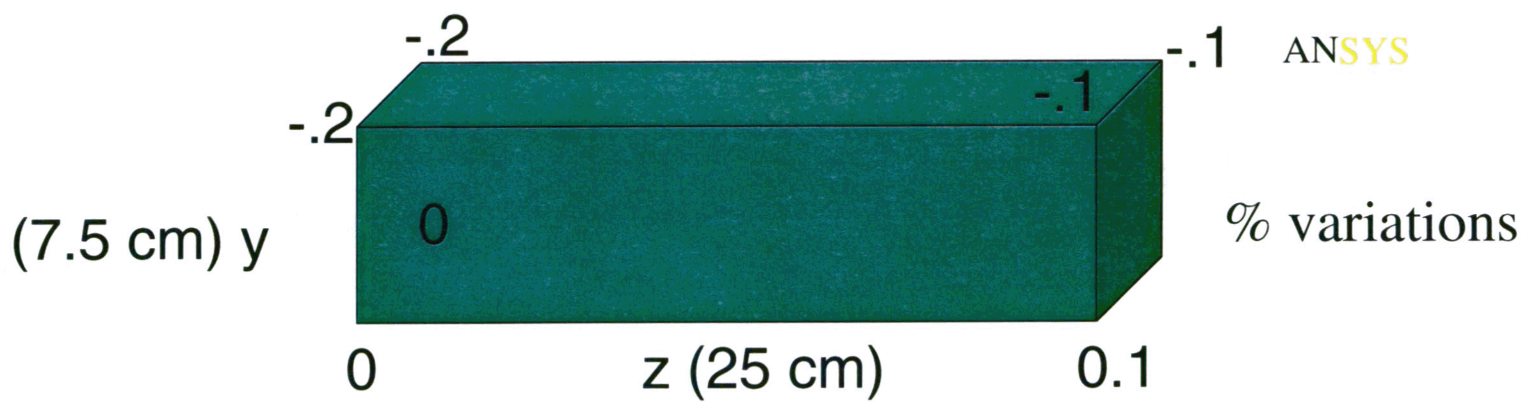
COSθ COIL



MAGNETIC FIELD CALCULATIONS

Coil: 30 cm radius x 120 cm half length

Superconducting Shield: 48 cm radius x 120 cm half length



Uniformity 0.1% over target cells achieved with non-uniform coil spacing

Next step - try to reduce dimensions of coil and shield

CALCULATIONS / MEASUREMENTS

- Optimization of cold neutron beam: Choppers, Bi, spin splitter, spin flipper, …
- Cold neutron flux and UCN production rate
- Polarized ^{3}He production rate, polarization, transfer to reservoir and cell, spin flip
- Ultra pure ^{4}He cycle
- Final neutron polarization process, RF coils, $\pi/2$ rotation
- n- ^{3}He absorption signal versus density and time; compared to background to 2000 s
- Photo-electrons at the PMT for ^{3}He absorption and β decay
- Polarized-n lifetime in the trap
- Polarized-^{3}He diffusion and lifetime in the trap
- SQUID signal and signal / noise at trap temperature; microphonics sensitivity
- Simulation
- Analysis of EDM sensitivity versus storage time including statistics and backgrounds
- Strategy for measurement sequence: spin and field reversals, empty cell
- Optimized B and E fields
- Maximum practical E field: HV source, stability
- Isolation from external E and B fields, superconductiong shield, trapped B fields
- Analysis of systematic errors

CONSTRUCTION COST

•Neutron guide and shielding	$ 620k
•Cryogenics	$1280k*
•^{3}He atomic beam source	$ 80k*
•Magnetic shielding	$ 415k
•Magnets	$ 217k
•High voltage	$ 370k*
•Measuring cell / SQUIDs	$ 250k
•Light system	$ 110k
•Electronics / computers	$ 110k
•Conventional construction	$ 940k
•Management, Engineering, and Integration	$1390k
•Total	$5835k
•Contingency @ 40%	$2334k
•Burdened @ 23.5% for construction	$1920k
•Escalation	$ 994k
•Grand total	$11083k

*Credit taken for equipment already purchased

SCHEDULE

FY'00	Tomography preparations
	DOE draft proposal started
FY'01	Neutron tomography at LANSCE - Distributions and ^{3}He diffusion coefficient
	DOE draft proposal 50% complete, engineering begins for proposal
FY'02	UCN rate demonstration, n-lifetime in bottle, polarized ^{3}He source, HV test
	Workshop, collaboration formation, proposal submission
FY'03-4	SQUID measurement of ^{3}He magnetization, ^{3}He polarization lifetime, trapped B
	Technical review of the conceptual design report
FY'05	Construction start
	Some experimental tests
FY'06	Construction
	Some experimental tests
FY'07	First Data for measuring the level of systematic errors
FY'08	Production data
FY'09	Production data or move to SNS
	First physics publication from EDM search
FY'10	Final physics publication from EDM search from LANSCE and SNS production

SENSITIVITY

$$\sigma_T(f) = \frac{1}{4\pi}\sqrt{\frac{12\tau_3(T_m + T_F)}{PV\left(1 - e^{-\frac{T_F}{\tau}}\right)T\tau^2\left(2\tau^2 - \left[T_m^2 + 2\tau T_m + 2\tau^2\right]e^{-\frac{T_m}{\tau}}\right)}}$$

Evaluate with P=1/cc/s, V=4 ℓ, T=100 d, E=50 kV/cm, 2 cells

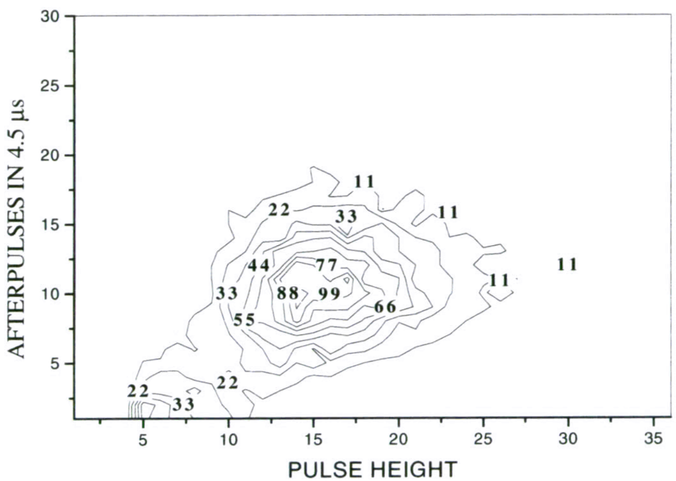
$\sigma_T(f)$=39.0 nHz with T_m=500 s, T_F=1000 s and τ_3=1000 s $\Rightarrow$
$d_n < 9 \times 10^{-28}$ e•cm (95% CL) -- with β-decay background only

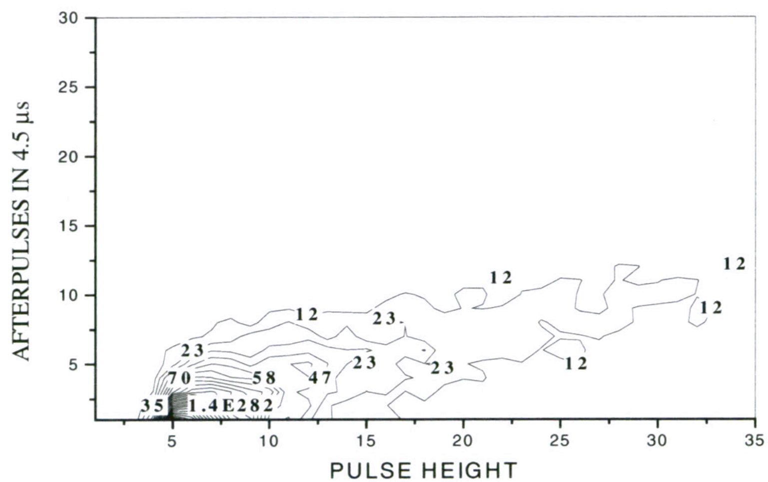
$\sigma_T(f)$=19.5 nHz with T_m=500 s, T_F=1000 s and τ_3=1000 s $\Rightarrow$
$d_n < 4.5 \times 10^{-28}$ e•cm (95% CL) -- with β-decays eliminated

$\sigma_T(f)$=8.2 nHz with with T_m=2850 s, T_F=1375 s and τ_3=2000 s $\Rightarrow$
$d_n < 2 \times 10^{-28}$ e•cm (95% CL) -- with β-decays eliminated

β-decay and γ-ray suppression

Neutron beam on 1.8-K He





Pure ^{4}He

^{4}He doped with ^{3}He

γ-rays from neutron activation

Choose the best materials, minimize the room background

Most Optimistic Result at SNS

$d_n < [2 \times 10^{-28}\ e \bullet cm\ (95\%\ CL)](100\text{-days}/300\text{-days})^{1/2}/5.4$

$d_n < 2 \times 10^{-29}\ e \bullet cm\ (95\%\ CL)$

At this level, systematic errors will need to be suppressed beyond our current design.